



Volume Bragg Grating for Coupling the Stokes Wave Out of an Amplifier

**by John E. McElhenny, Jeffrey O. White,
Steven D. Rogers, and Tigran Sanamyan**

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14. ABSTRACT <p>High power multimode fiber (MMF) master-oscillator power amplifiers (MOPAs) with stimulated Brillouin scattering (SBS) beam cleanup and wavefront reversal are under development at the U.S. Army Research Laboratory (ARL) to counter rockets, artillery, and mortar (CRAM). When Faraday isolators are used for outcoupling the Stokes light in the MMF MOPAs, the power scalability is limited. Volume Bragg gratings (VBGs) appear to be more scalable. We report here the results of tests on a VBG designed to separate wavelengths 0.0604 nm (16 GHz) apart, corresponding to the SBS frequency shift at 1064 nm in fused silica.</p>					
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1. Introduction/Background

High power multimode fiber (MMF) master-oscillator power amplifiers (MOPAs) with stimulated Brillouin scattering (SBS) beam cleanup and wavefront reversal are under development at the U.S. Army Research Laboratory (ARL) for counter rockets, artillery, and mortar (CRAM).

In the wavefront reversal geometry (figure 1), a Faraday rotator-polarizer combination (Faraday isolator) couples the oscillator into the amplifier, and outcouples the amplified Stokes light. During the first pass through the large mode area (LMA) fiber core, the incident fundamental mode from the oscillator is amplified and scattered into multiple spatial modes. This light is coupled into a fiber designed to generate a wavefront reversed and frequency-shifted backscattered Stokes beam through SBS (I). As it propagates back through the LMA fiber (second pass), the scattering is undone and the fundamental mode quality is restored. A component is needed that transmits the laser light (into the fiber) and redirects the Stokes light (from the fiber). There is little basis by which to separate the two beams; the polarizations may be identical and the wavelengths differ by less than one part in 10^5 . Faraday isolators distinguish between the two beams based on the fact that they are counter-propagating. Volume Bragg gratings (VBGs) distinguish between the two beams based on the different wavelengths, as in a conventional diffraction grating.

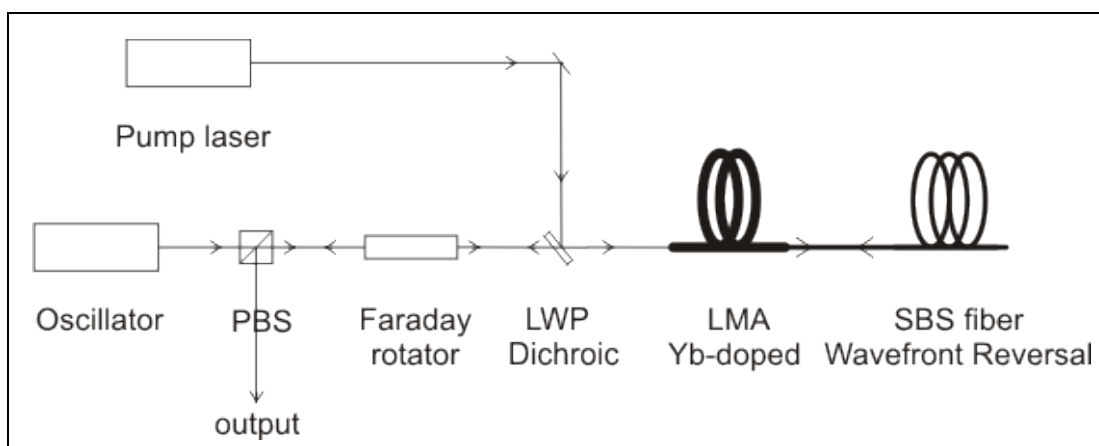


Figure 1. The experimental setup for the high power MMF MOPA with phase conjugation. The Faraday rotator is the limiting factor.

The highest power commercial-off-the-shelf Faraday isolators can handle only up to 1 kW (2). Compared to Faraday isolators, VBGs are a more scalable option for outcoupling the Stokes beam. At 1064 nm in fused silica, the wavelength shift of 0.0604 nm (16 GHz) is only one part in $\sim 17,600$, so to resolve the two wavelengths, i.e., reflect the laser wavelength and transmit the Stokes wavelength, the VBG must have $\sim 17,600$ periods. A reflection grating of period 532 nm

in a material of index 1.49 (photo-thermal refractive [PTR] glass) would require a thickness of at least 6 mm. For a grating of thickness 12 mm, the anticipated reflectance (figure 2) was ~ 0.95 at λ_L and ~ 0.05 at λ_S (transmittance ~ 0.95). The blue line corresponds to illumination with a plane wave; the red line corresponds to a more realistic beam with 0.4-mrad divergence.

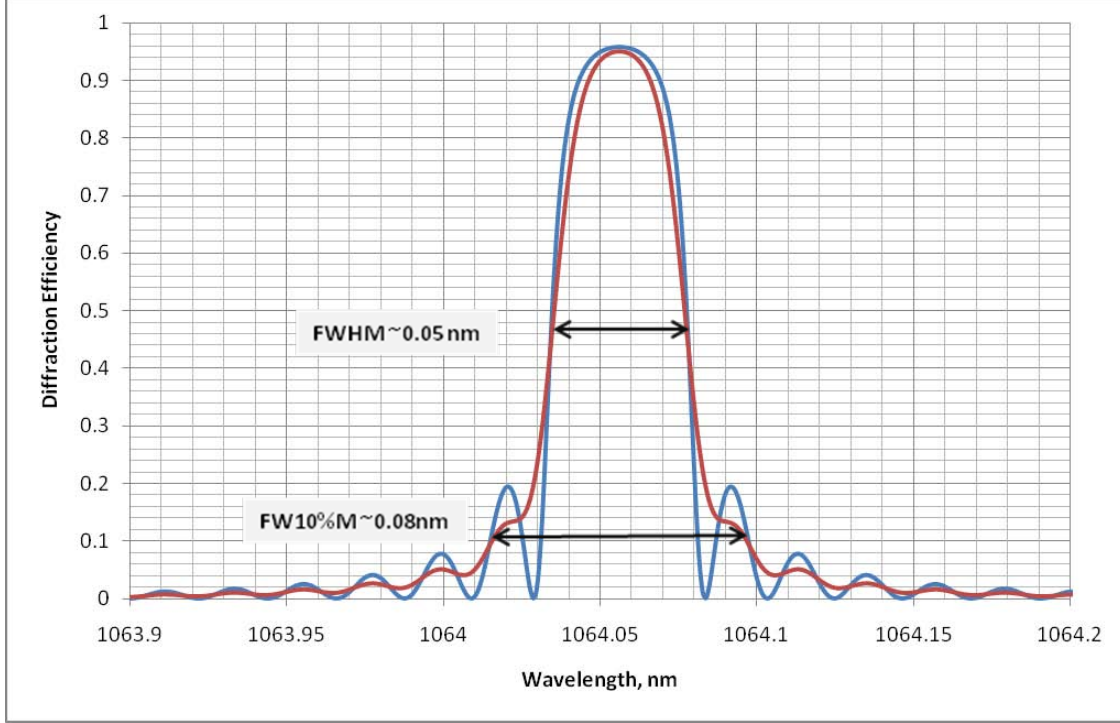


Figure 2. Anticipated spectral response of volume Bragg grating from OptiGrate (3).

2. Experiment/Calculations

In the *wavefront reversal* MOPA geometry, the Stokes beam is coupled out after the second pass amplification. The safest approach is to reflect the laser beam and transmit the Stokes beam (figure 3) rather than vice versa, because if the VBG shifts, the input light will not be coupled into the amplifier and no high-power 1064-nm beam will be created. In the *beam cleanup* MOPA geometry, the Stokes beam is outcoupled immediately after the SBS takes place and there is no preferred approach regarding safety; it does not matter which beam is transmitted and which is reflected. For ease of alignment, we transmit the laser beam and reflect the Stokes (figure 4).

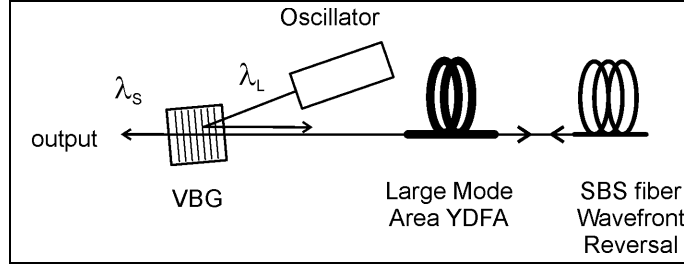


Figure 3. Using a VBG to outcouple in the wavefront reversal geometry. This geometry is safer than transmitting λ_L and reflecting λ_S .

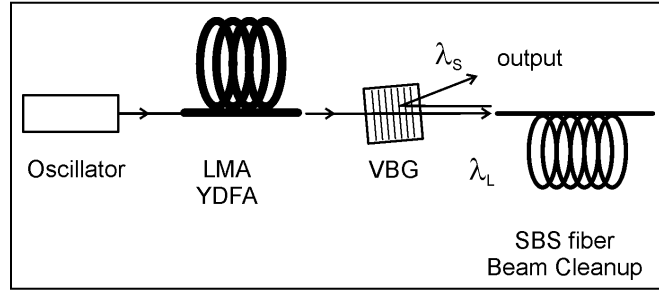


Figure 4. A possible configuration to outcouple in the beam cleanup geometry. It is equally appropriate to reflect λ_L and transmit λ_S .

One issue is whether absorption will heat the VBG enough to shift the resonance. The index change and thermal expansion of PTR glass are such that the resonant wavelength red shifts $\sim 0.007 \text{ nm/}^\circ\text{C}$. To investigate this we solved the three-dimensional (3-D) heat diffusion equation inside an $8 \times 10 \times 16.5 \text{ mm}^3$ piece of glass with specific heat $0.84 \text{ J/gm}^\circ\text{K}$ and thermal conductivity 1 W/mK . An absorption coefficient $\alpha = 10^{-3} \text{ cm}^{-1}$ corresponds to an absorbed power of 0.16% of the incident power. Obtaining a 100-W average power from the MOPA is the goal of our Joint Technology Office (JTO) contract supporting this research. We, therefore, assume that 0.16 W is deposited uniformly in a cylinder 6 mm in diameter and 16.5 mm long. The boundary conditions are that two surfaces are in contact with a heat sink at 300 K. The steady-state results show a 1°C temperature difference between the beam axis and the 3-mm radius of the beam (figures 5 and 6). This implies a 0.007-nm shift in resonance, which will produce only a small change in the transmission at λ_L and λ_S .

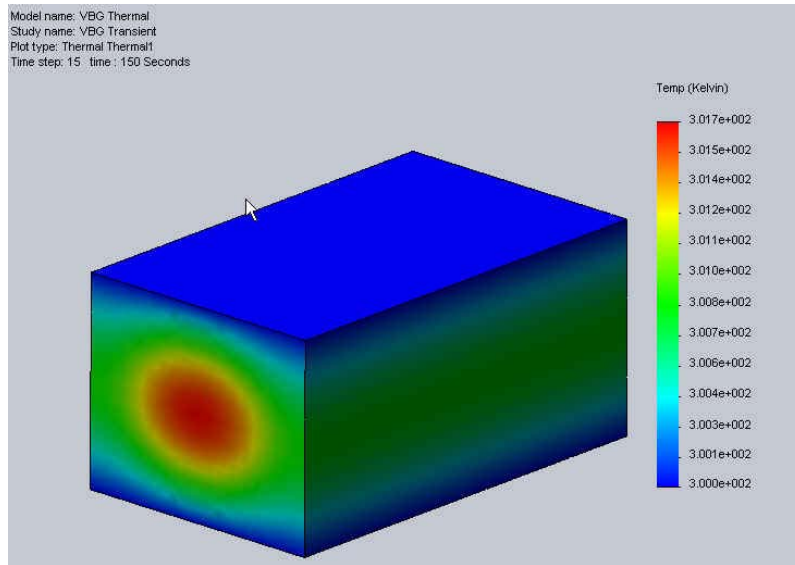


Figure 5. Steady-state temperature profile inside an $8 \times 10 \times 16.5 \text{ mm}^3$ piece of PTR glass, with 0.16 W of heat deposited in a cylinder of the same length and 6 mm in diameter.

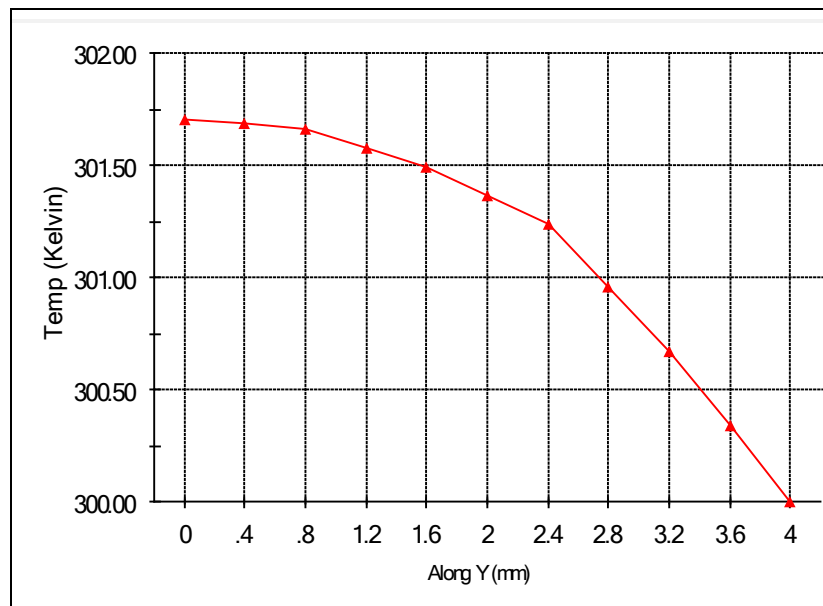


Figure 6. Steady-state VBG temperature vs. distance along the y-axis from the center of figure 5.

The thermal time constant on the order of 1 min limits the rate at which the output power of the laser can be changed (figure 7).

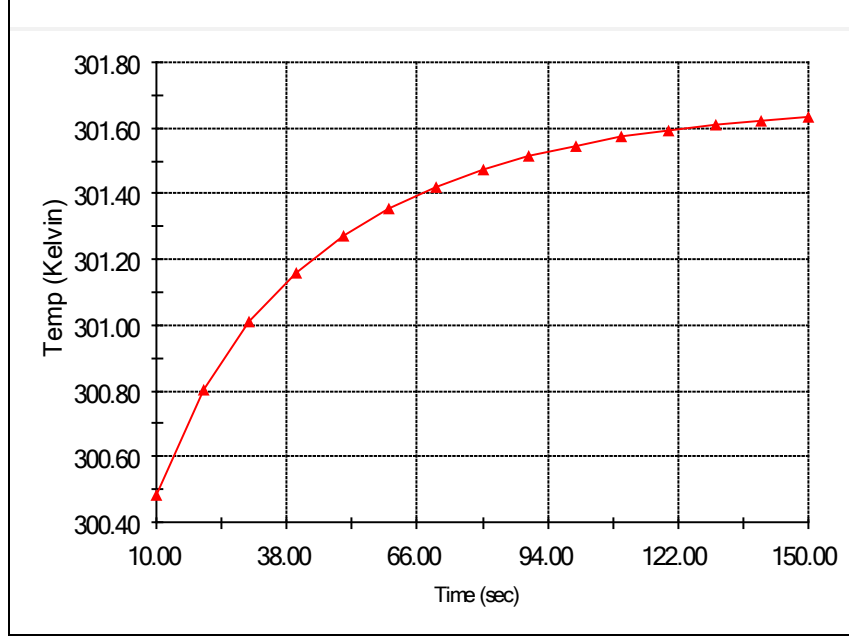


Figure 7. Transient VBG temperature on axis with the same conditions as figure 5.

The size of the actual VBG is state-of-the-art at $8 \times 10 \times 12 \text{ mm}^3$ and mounted in a temperature-controlled holder (figure 8). To test the VBG, we used a setup (figure 9) in which the laser light is reflected and the Stokes light is transmitted. This is the preferred setup for the wavefront reversal geometry and will also work for beam cleanup.

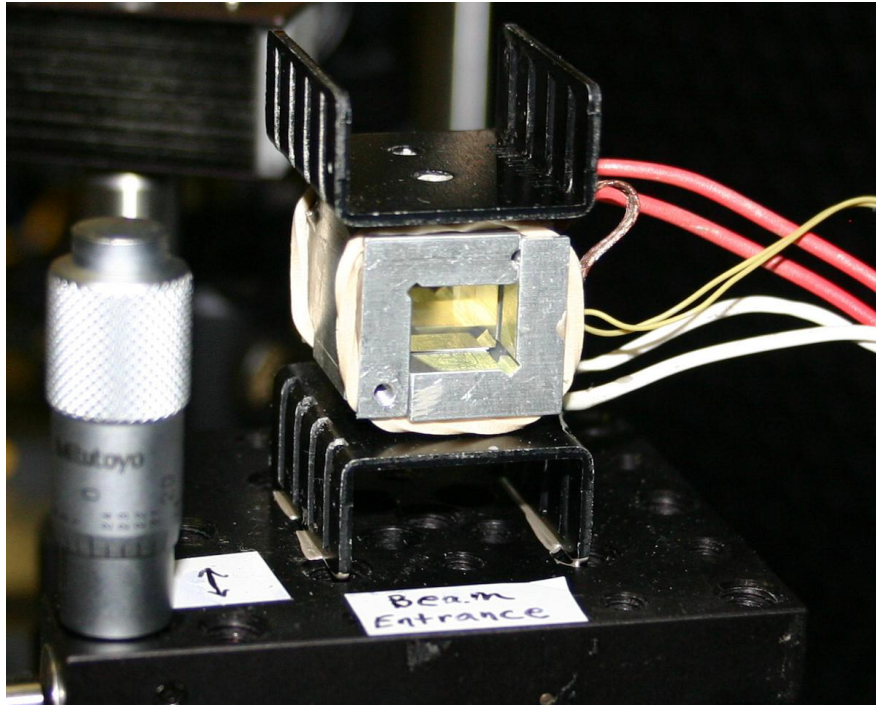


Figure 8. The VBG in its temperature-controlled holder and mounted to a tip-tilt stage.

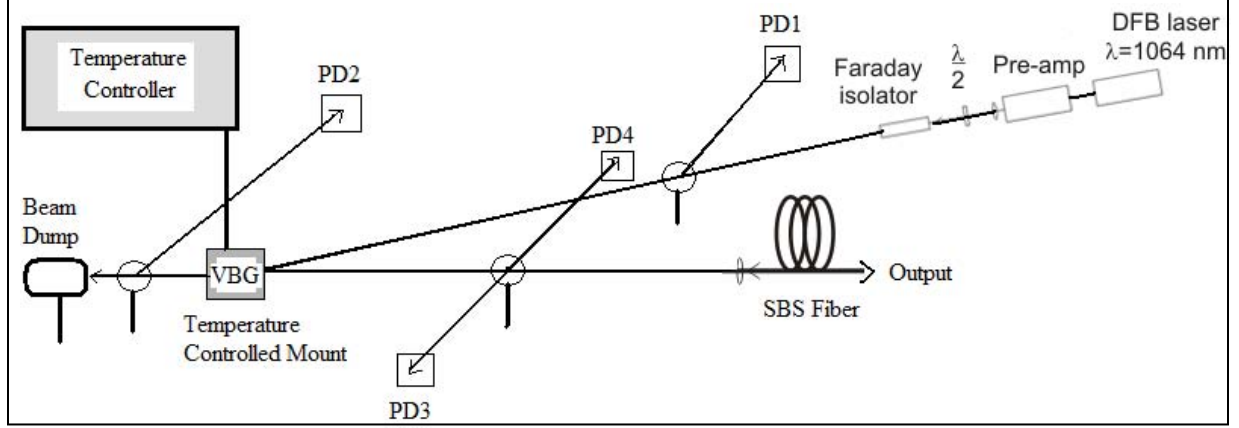


Figure 9. Experimental setup to test ability of VBG to decouple the Stokes from the input wave.

We collimate the input light with a 35-mm focal length doublet (to a 4.9-mm-diameter beam), use the half-waveplate and Faraday isolator as a variable optical attenuator (VOA) and couple into the fiber with a 19-mm focal length doublet. Uncoated beam samplers at a small angle of incidence monitor the power. The input angle and the VBG angle are chosen to maximize the Bragg reflection of the input light.

3. Results and Discussion

The threshold of the OFS graded-index (GI) 50/125 fiber is 0.2 W. The VBG reflectance of the input light (λ_L) is 85% while the maximum VBG transmittance of the Stokes light (λ_S) is ~84%. The VBG Stokes transmittance is calculated from

$$T_{Stokes}^{VBG} = \frac{P_{trans}^{VBG} - (1 - R_{laser}^{VBG})0.04P_{refl}^{VBG}}{P_{back}^{fiber} - 0.04P_{refl}^{VBG}} \quad (1)$$

where P_{trans}^{VBG} is the power transmitted through the VBG from the fiber (PD2), P_{refl}^{VBG} is the input laser power reflected by the VBG (PD3), R_{laser}^{VBG} is the reflectance of the VBG at the laser wavelength, P_{back}^{fiber} is the backscattered power (both the SBS-generated Stokes wave and Fresnel reflection) from the fiber (PD4), and 0.04 corresponds to the Fresnel reflection from the input face of the fiber.

Figure 10 shows the input laser power reflected by the VBG, the input laser power to the SBS fiber, the Fresnel reflected and backscattered Stokes power, and the Fresnel and Stokes power transmitted through the VBG, as well as the VBG reflectance at λ_L , VBG Stokes transmittance at λ_S , and SBS reflectance.

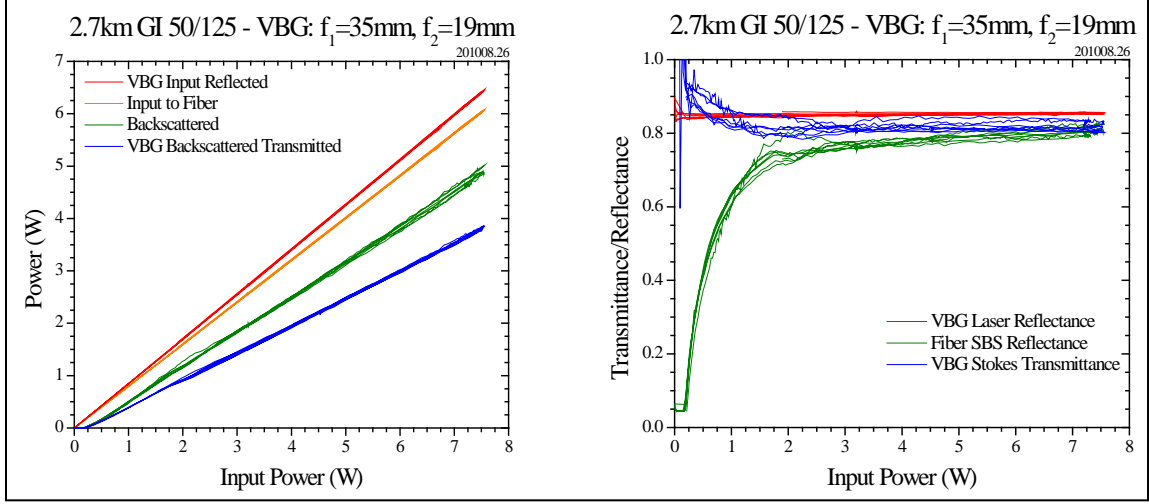


Figure 10. (a) The input laser power reflected by the VBG (red, PD3), the input laser power to the SBS fiber (orange), the Fresnel reflected and backscattered Stokes power (green, PD4), and the Fresnel and Stokes power transmitted through the VBG (blue, PD2); and (b) the VBG reflectance at λ_L (red), VBG Stokes transmittance at λ_S (blue), and SBS reflectance (green).

4. Conclusions

The scalability of the high-power MMF MOPAs was previously limited by the Faraday isolators available, which can handle a maximum of 1 kW. Compared to a Faraday isolator, a VBG made from PTR glass appears to be a more scalable option for outcoupling the Stokes beam.

The VBG, fabricated by OptiGrate (3), is designed to separate wavelengths 0.0604 nm apart (the wavelength shift between the input and Stokes waves operating at 1064 nm in fused silica). It reflects up to 85% of the input laser light while transmitting up to 84% of the backscattered Stokes light. Faraday isolators outcouple based on the direction of propagation, while VBGs outcouple based on the wavelength difference between the two waves.

5. References

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List of Symbols, Abbreviations, and Acronyms

3-D	three-dimensional
ARL	U.S. Army Research Laboratory
CRAM	counter rockets, artillery, and mortar
GI	graded-index
JTO	Joint Technology Office
LMA	large mode area
MMF	multimode fiber
MOPA	master-oscillator passive-amplifier
PTR	photo-thermal refractive
SBS	stimulated Brillouin scattering
VBG	volume Bragg grating
VOA	variable optical attenuator

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